Recent progress in rechargeable batteries enabling future transportation

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Present-day Energy Chain

Power plant

Research
Future Sustainable Energy Chain

Wind

Power plant

Solar

µ-Heat-Power

Heat pumps
Residential Storage

Fluctuating sources Require ~20% storage...!
“Electrical vehicles”: The dream
Plug-in Electric 2-Wheelers already widely accepted in Eastern Asia

Figure 21. Fully electric personal mobility options: (a) Urban Mover electric bicycle, (b) Vectrix electric scooter, (c) Enertia electric motorcycle, (d) Segway Personal Transporter.
Plug-in (Hybrid) Electrical Vehicles

Electric Vehicle (EV)

Plug-in Hybrid Electrical Vehicles (PHEV)

Figure 19. A range of full battery-electric vehicles including (a) India’s Reva, (b) Chinese made Miles ZX40S, (c) Norway’s Think City, and (d) US’s Tesla Roadster.

Figure 20. A selection of PHEVs, ranging from (a) Prius+, driven daily by CalCars founding member Felix Kramer, to various concepts which have debuted in recent Motor Shows: (b) Chevrolet Volt, (c) Opel Flexextreme, (d) Volvo ReCharge.
Plug-in (Hybrid) Electrical Vehicles

Advantages:
• Much more efficient than ICE (> 2x)
• Significant reduction in CO$_2$ emissions (< 2x)
• Zero emission with sustainable energy sources…!
• Environmental friendly, no urban pollution…!
• Cost effective during life-time already now…!
• Grid stabilization *versus* electricity trading
• Silent driving…!

Disadvantages:
• High initial investment
• Limited driving range
• Recharging time not “instantaneous”
• Silent driving…!
Plug-in (Hybrid) Electrical Vehicles

**AMERICAN DRIVING PATTERNS**

- **Figure 17.** Half of all personal automobiles in the US travel 25 miles (40 km) or less each day, while eighty percent travel a maximum of 50 miles (80 km).165

Source: EPRI Journal, Fall 2005

P(H)EV Storage

“Residential storage” in Electrical Vehicles
Electricity storage

**Physical**
- Super-capacitors
- Pseudo-capacitors

**Electrochemical**
- Batteries
- Redox-flow cells
- Metal-air systems
Physical storage in (Super)capacitors

Based on Electrochemical double layers

\[ C = \frac{\varepsilon\varepsilon_0 A}{d} \]
Electricity storage

Physical
- Super-capacitors
- Pseudo-capacitors

Electrochemical
- Batteries
- Redox-flow cells
- Metal-air systems
# Rechargeable battery chemistries

<table>
<thead>
<tr>
<th>System</th>
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<tbody>
<tr>
<td>• Sealed Lead Acid (SLA)</td>
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<tr>
<td>• NiCd</td>
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<tr>
<td>• NiMH</td>
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## Rechargeable battery chemistries

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<th>Advantages</th>
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<tr>
<td>Sealed Lead Acid (SLA)</td>
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<td>Heavy</td>
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<td></td>
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<td>Overdischarge</td>
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<tr>
<td>NiCd</td>
<td>Power density</td>
<td>Pollution</td>
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<tr>
<td>NiMH</td>
<td>Energy density</td>
<td>Gas formation</td>
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<td>- Volumetric</td>
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<td>- Gravimetric</td>
<td>Electronics</td>
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<td>- Control</td>
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Two ways to form a hydride

1. Gas phase

$$\text{H}_2 \text{ gas} \quad \text{Solid}$$

$$\text{H}_2 \xrightarrow{\text{dis}} 2\text{H}_{\text{ad}} \quad \text{diffusion} \quad 2\text{H}_{\text{abs}} (\text{Hydride})$$

Research
New Hydrogen storage materials for
- future hydrogen economy?
- new generation NiMH batteries?
Two ways to form a hydride

1. Gas phase

\[ \text{H}_2 \text{ gas} \quad \text{Solid} \quad 2\text{H}_{\text{ad}} \]

\[ \text{H}_2 \xrightarrow{\text{dis}} 2\text{H}_{\text{ad}} \quad \text{diffusion} \quad 2\text{H}_{\text{abs}} \text{(Hydride)} \]

2. Electrochemically

Electrolyte

\[ \text{H}_2\text{O} + \text{e}^- \xrightarrow{\text{red}} \text{OH}^- + \text{H}_{\text{ad}} \]

Electrode

\[ \text{H}_{\text{abs}} \text{(Hydride)} \]

Research
NiMH battery concept

Nickel electrode
- $e^-$
- $H_2O$
- NiOOH
- Ni(OH)$_2$
- OH$^-$

Hydride electrode
- $xOH^-$
- $MH_x$
- $M$
- $xH_2O$
- $xe^-$

Separator impregnated with KOH solution

Capacity
Thermodynamics and kinetics of batteries
Thermodynamics and kinetics of batteries

\[ \text{Ni(OH)}_2 + \text{OH}^- \xrightleftharpoons{\text{ch}} \text{NiOOH} + \text{H}_2\text{O} + \text{e}^- \]

\[ \text{M} + \text{H}_2\text{O} + \text{e}^- \xrightleftharpoons{\text{ch}} \text{MH} + \text{OH}^- \]

\[ I_a \]

\[ I_{a}^o \]

\[ I_{\text{MH}} \]

\[ I_{c} \]

\[ \eta_{\text{MH}} \]

\[ \text{open-circuit potential} \]

\[ \eta_{\text{Ni}} \]

\[ E_e \]

\[ E \ [\text{V}] \ vs \ \text{Hg/HgO} \]
NiMH battery concept

**Overcharge**

\[
4 \text{OH}^- \xrightarrow{\text{Ni}} 2\text{H}_2\text{O} + \text{O}_2 + 4\text{e}^- 
\]

**Hydride electrode**

\[
\text{MH}_x \xrightarrow{\text{MH}} \text{M} + x\text{H}_2\text{O} + xe^- 
\]

**Nickel electrode**

\[
\text{Ni(OH)}_2 \xrightarrow{\text{Ni}} \text{NiOOH} + \text{OH}^- + e^- 
\]

**Separator impregnated with KOH solution**

**Capacity**

\[
\text{H}_2 \xrightarrow{\text{H}_2} \text{OH}^- \quad \text{ch} \quad \text{d} 
\]

**Overdischarge**

\[
2\text{e}^- + 2\text{H}_2\text{O} \xrightarrow{\text{Ni}} 2\text{OH}^- + \text{H}_2 
\]
Simple CC-charging NiMH batteries

- Voltage ($E$) vs. State-of-charge
- Temperature ($T$) vs. State-of-charge
- Pressure ($P$) vs. State-of-charge

Graph shows the variation of voltage, temperature, and pressure with state-of-charge.
Li-ion battery concept

lithium electrode

CoO$_2$

LiCoO$_2$

cobalt oxide electrode

LiC

storage capacity

charge
discharge

charge

discharge

Research
Li-ion battery concept

**lithium electrode**

| LiC | C | Li^+ | e^- |

**storage capacity**

| LiCoO_2 | e^- | Li^+ |

**cobaltoxide electrode**

**charge**

**discharge**
More complex CCCV charging Li-ion

![Graph showing voltage and current over time for Li-ion charging. The graph includes two distinct regions, (a) and (b), with maxima and minima labeled as $V_{\text{max}}$, $I_s^{\text{max}}$, and $I_s^{\text{min}}$. Time is measured in minutes, and voltage and current are measured in volts and amperes, respectively.]
Impact CV-charging on cycle-life

- Standard-CCCV
- CV=4.3 V
- CV=4.2 V
# Periodic Table of Elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
<th>Atomic Number</th>
<th>Atomic Weight</th>
</tr>
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<tbody>
<tr>
<td>Cerium</td>
<td>Ce</td>
<td>58</td>
<td>140.12</td>
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## Atomic Number vs. Atomic Weight

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## Periodic Table

![Periodic Table](image-url)
Efficiency rechargeable batteries excellent

Not affected by an inefficient Carnot cycle

\[ \eta = 1 - \frac{T_{\text{cold}}}{T_{\text{hot}}} \]

Discharge voltage curves as \( f(I) \)

New generation LiTiO\(_2\) + LiMn\(_2\)O\(_4\) batteries
Efficiency rechargeable batteries

Not affected by an inefficient Carnot cycle

Discharge voltage curves as f(I)

Discharge Efficiency as f(I)

Research

New generation LiTiO$_2$ + LiMn$_2$O$_4$ batteries
Well-to-wheel efficiency
Internal Combustion Engine (ICE)

\[ \eta_{\text{ICE}} \approx 17\% \]

*In accordance with IEA WTW report 2007*